Daya Bay

Steve Kettell
BNL

1) Motivation
2) Daya Bay Experiment
3) Daya Bay Project
4) BNL involvement

The Last Mixing Angle: θ_{13}

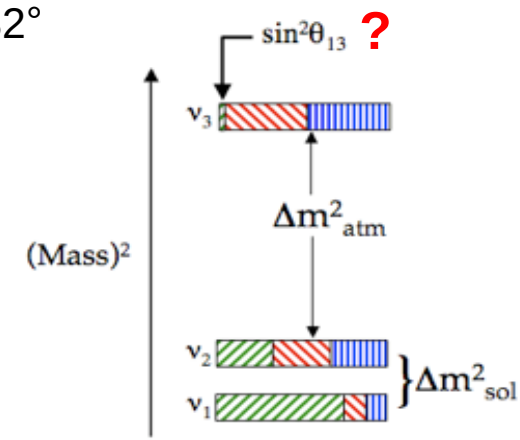
U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad ?$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$

θ_{23} = ~ 45° — θ_{13} = ? — θ_{12} ~ 32°



What is ν_e fraction of ν_3?
Is there μ–τ symmetry in neutrino mixing?
U_{e3} is the gateway to leptonic CP violation.

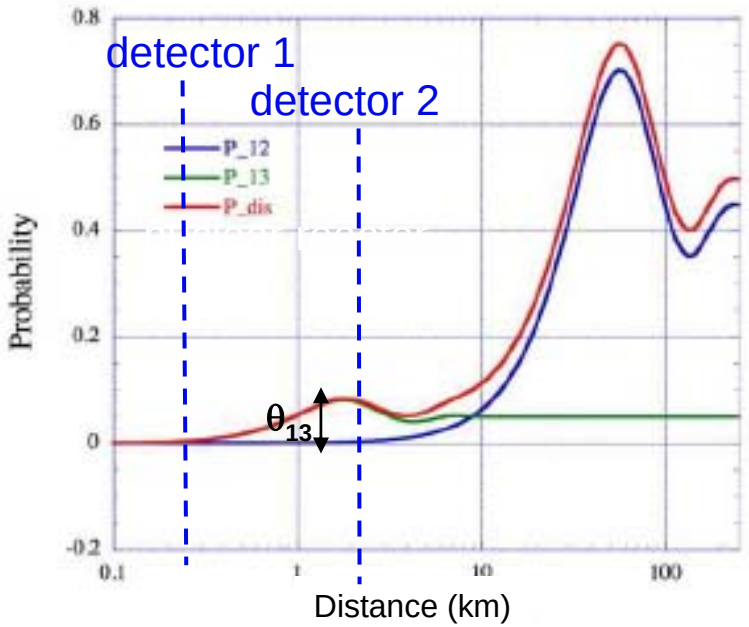
Why BNL?

- The Physics is compelling! and a critical step to ~~CP~~
- BNL provides a strong National Laboratory presence to assure the success of the experiment.
- BNL has a rich tradition in ν physics: in both the Physics and Chemistry departments
- BNL Chemistry has been involved in liquid scintillator research for Daya Bay for 3 years
- This experiment is a good match to the existing Physics Department effort on MINOS and future long-baseline experiment to measure CP violation in the neutrino sector.

Measuring $\sin^2 2\theta_{13}$ with Reactor Neutrinos

$$P_{ee} \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

- No dependence on δ_{CP} or matter effects
- Cost effective
- Rapid deployment possible



Detection of antineutrinos in liquid scintillator

- inverse β-decay in Gd-doped liquid scintillator:

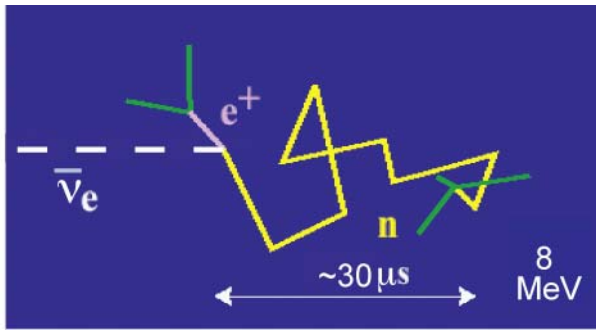
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$

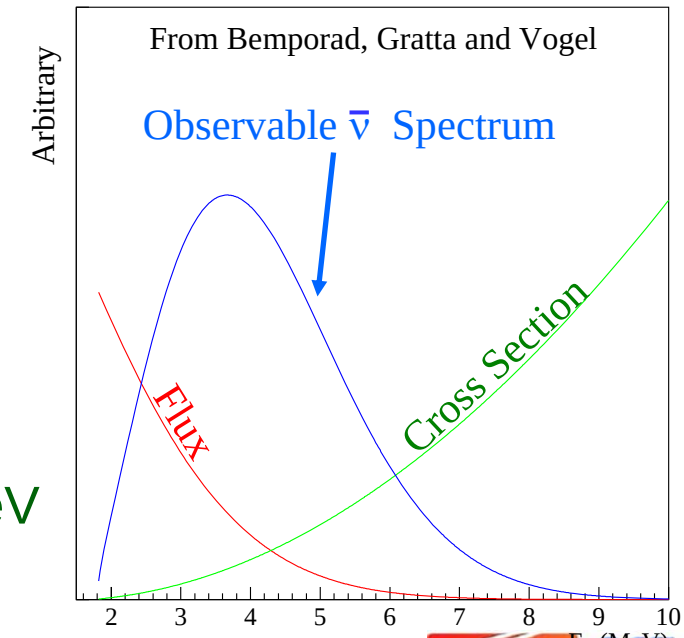
0.1% Gd

0.3b $\rightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed)

50,000b $\rightarrow + Gd \rightarrow Gd^*$

$\rightarrow Gd + \gamma$'s(8 MeV) (delayed)





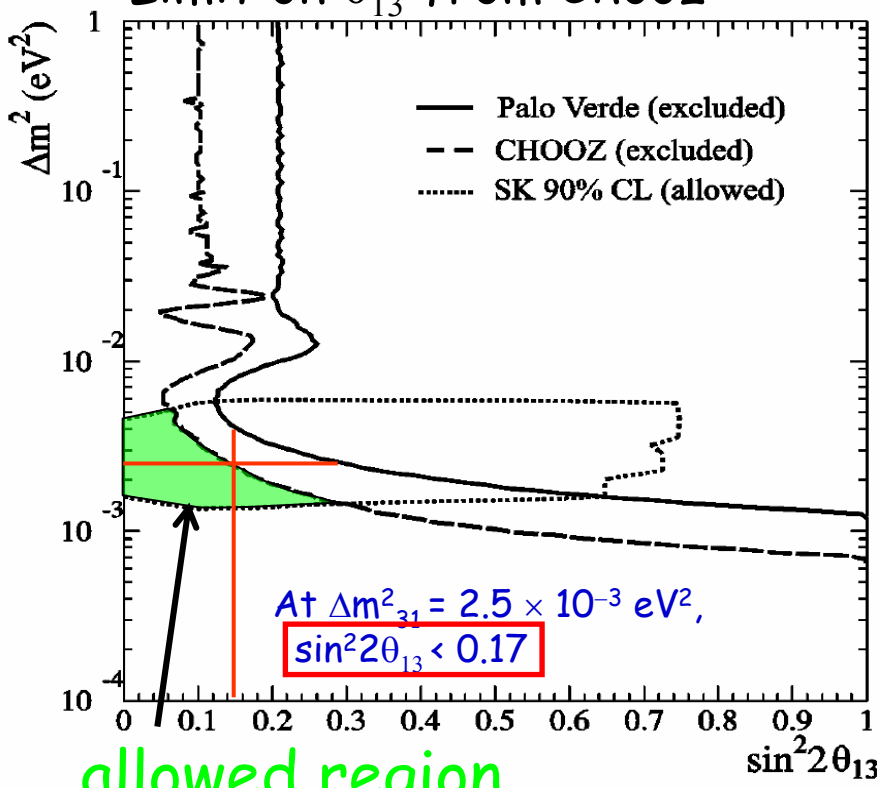
- Time- and energy-tagged signal is a good tool to suppress background events.
- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8\ \text{MeV}$$

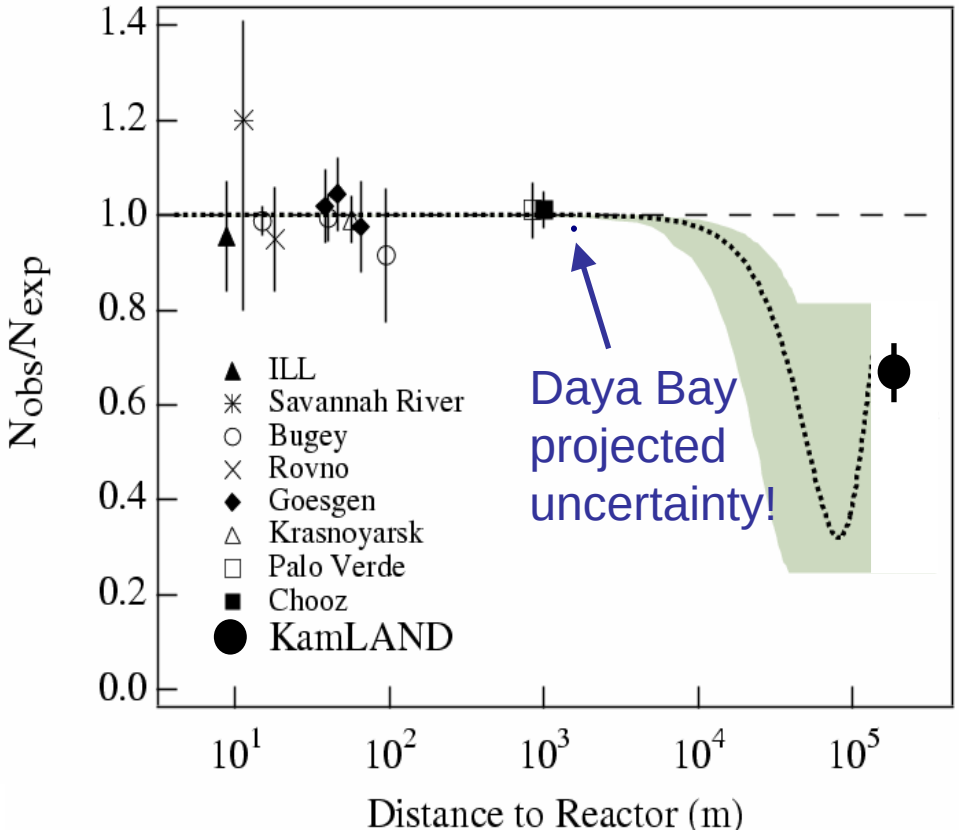
10-40 keV

Current Knowledge of θ_{13}

Limit on θ_{13} from Chooz



allowed region



~3000 events in 335 days
2.7% systematic error
without near detectors

Daya Bay takes ~1 week

Sensitivity to $\sin^2 2\theta_{13} \leq 0.01$

High statistics:

- Powerful reactor cores
- Large target mass

Control of systematic errors:

- Utilize multiple detectors at different baselines (near and far)
  $\rightarrow$ measure RATIOS
- Make detectors as nearly IDENTICAL as possible
- Careful and thorough calibration and monitoring of each detector
- Optimize baseline for best sensitivity and small residual reactor-related errors
- Possible to interchange detectors to further cancel most detector systematics

Measure ratio of detector rates:

$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

Measured Ratio of Rates

Detector Mass Ratio, H/C

Fill in pairs, load cells, Coriolis mass flow to 0.2% repeatibility

Detector Efficiency Ratio

$\sin^2 2\theta_{13}$

Requirement: **know relative efficiencies, each to 0.2%.**

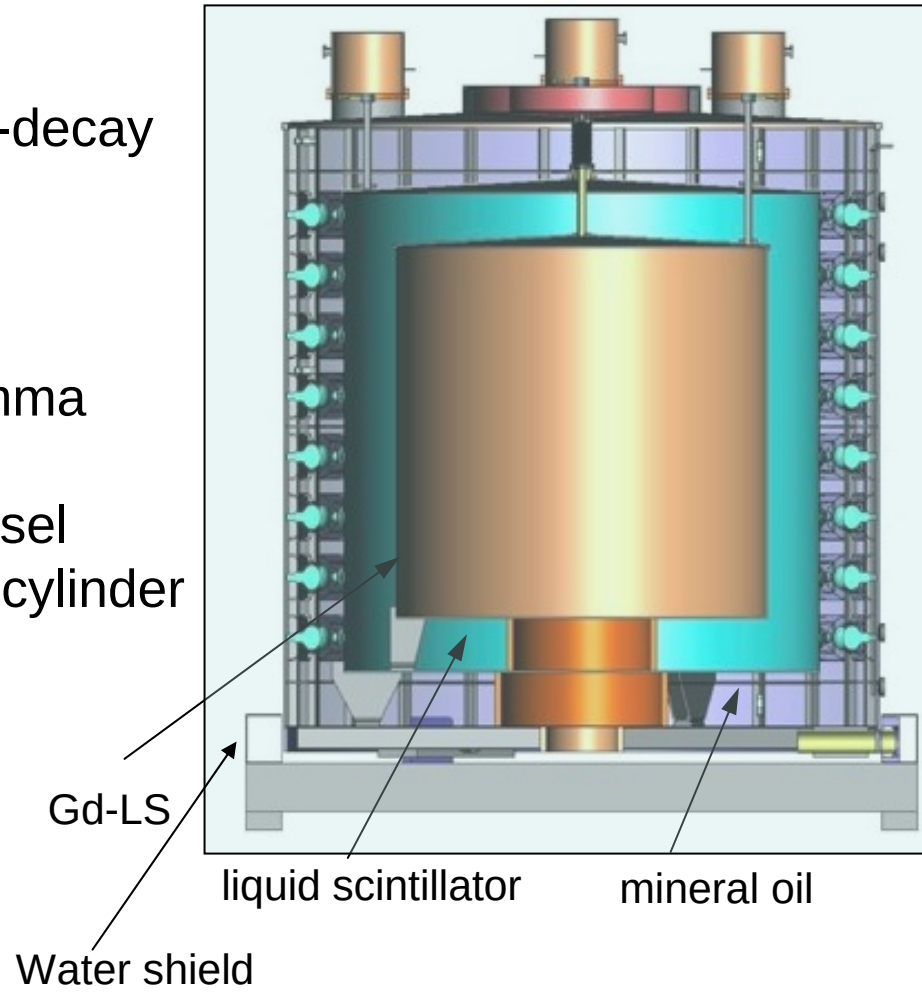
Antineutrino Detector

- Antineutrinos are detected via inverse β-decay in Gd-doped liquid scintillator (LS)

Description:

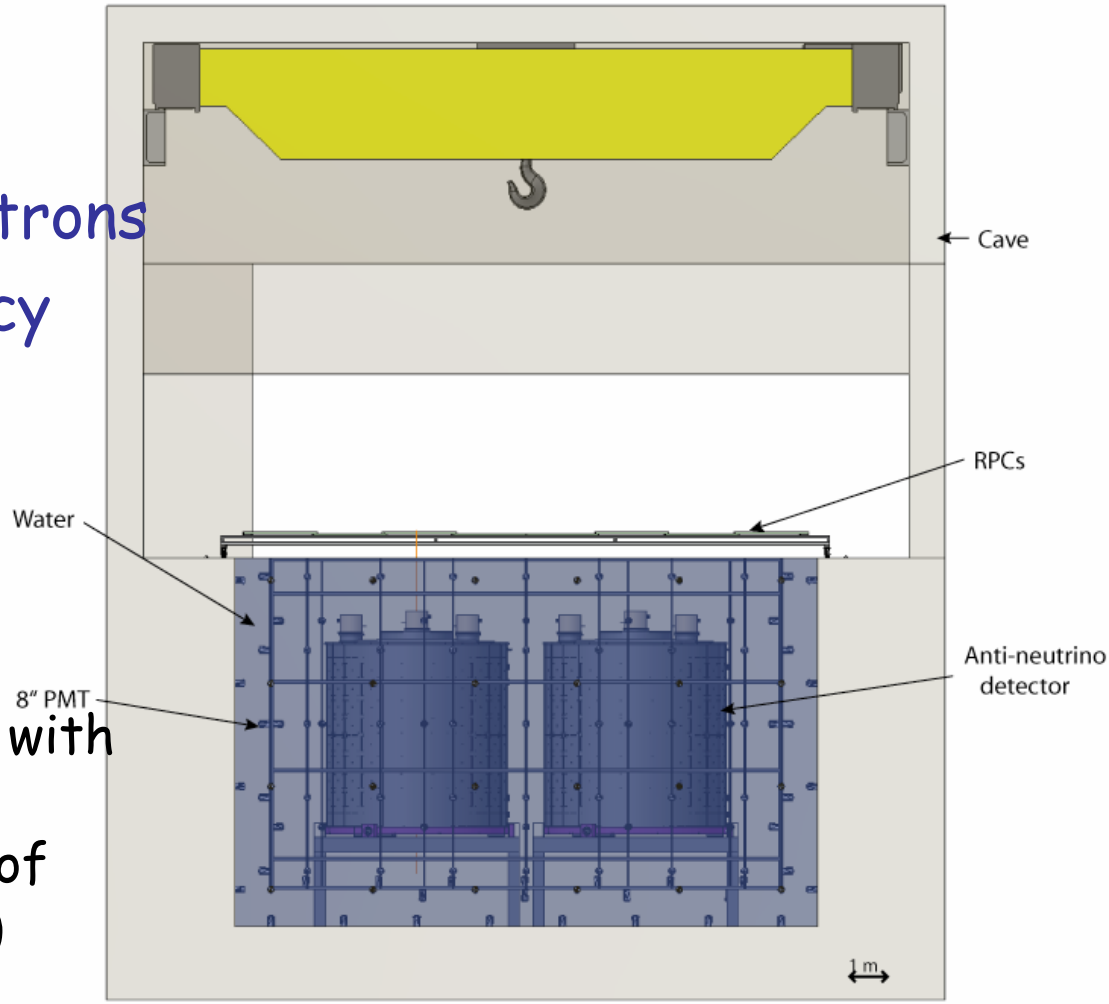
- 3 zones: Gd-LS target (20 tons), LS gamma catcher, oil buffer
- 2 nested acrylic vessels, 1 stainless vessel
- 192 PMT's on circumference of 5m×5m cylinder
- reflectors on endplates of cylinder
- energy resolution:

$$\frac{\sigma}{E} \sim \frac{11.6\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 12.5\mathrm{cm}$$



Muon System

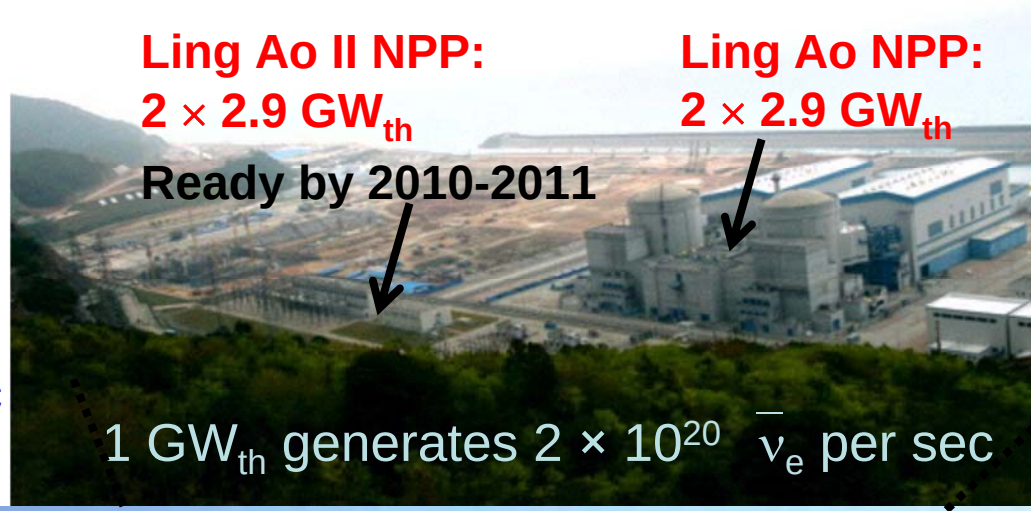
- Muon Veto
  - suppress spallation neutrons
  - require 99.5% efficiency
- Water shield (2.5m)
  - rock neutrons
  - radioactivity

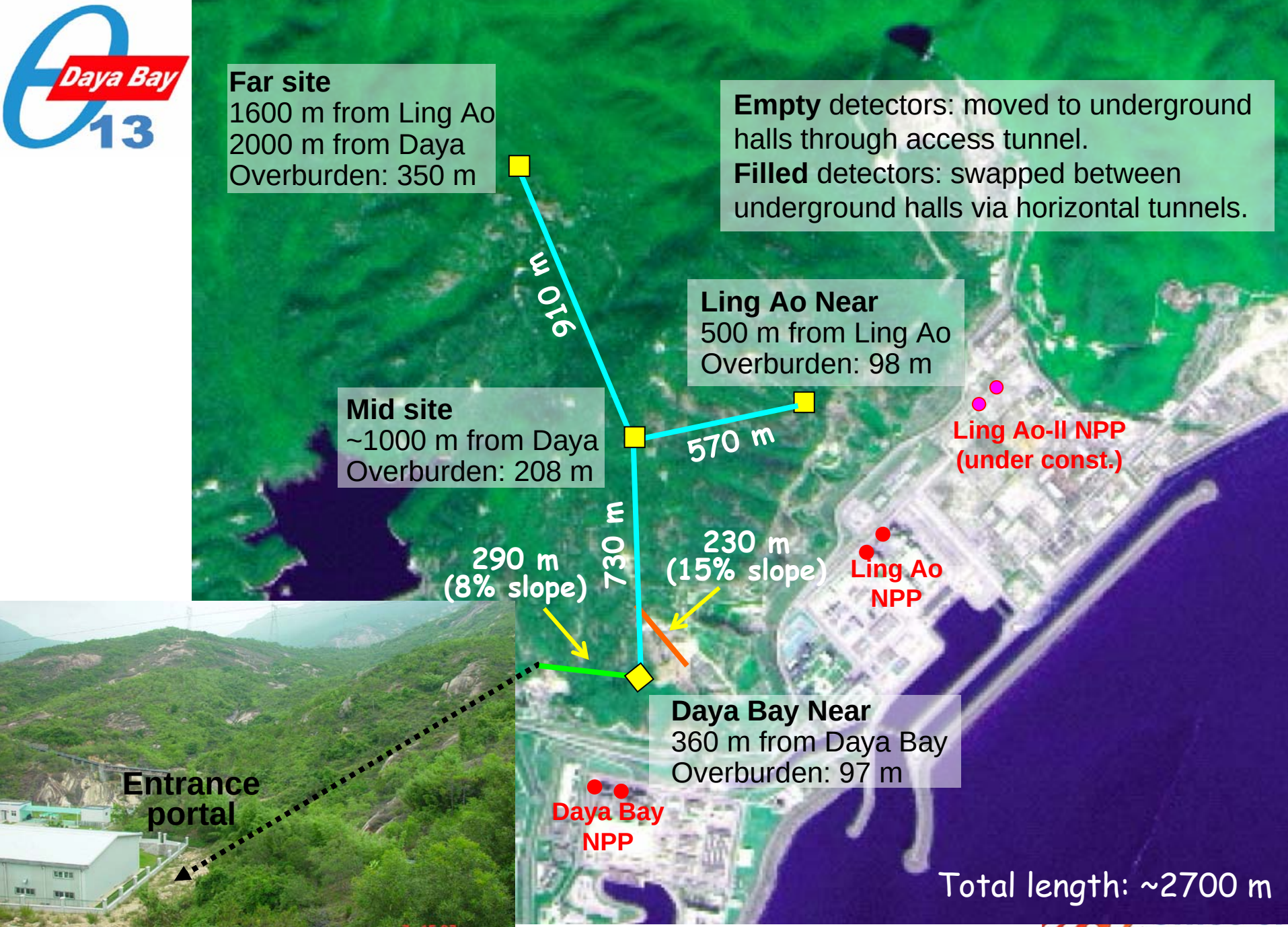


- Water Cherenkov detectors with 963 PMTs in 3 sites
- 756 RPC chambers over top of 3 pools (6048 readout strips)

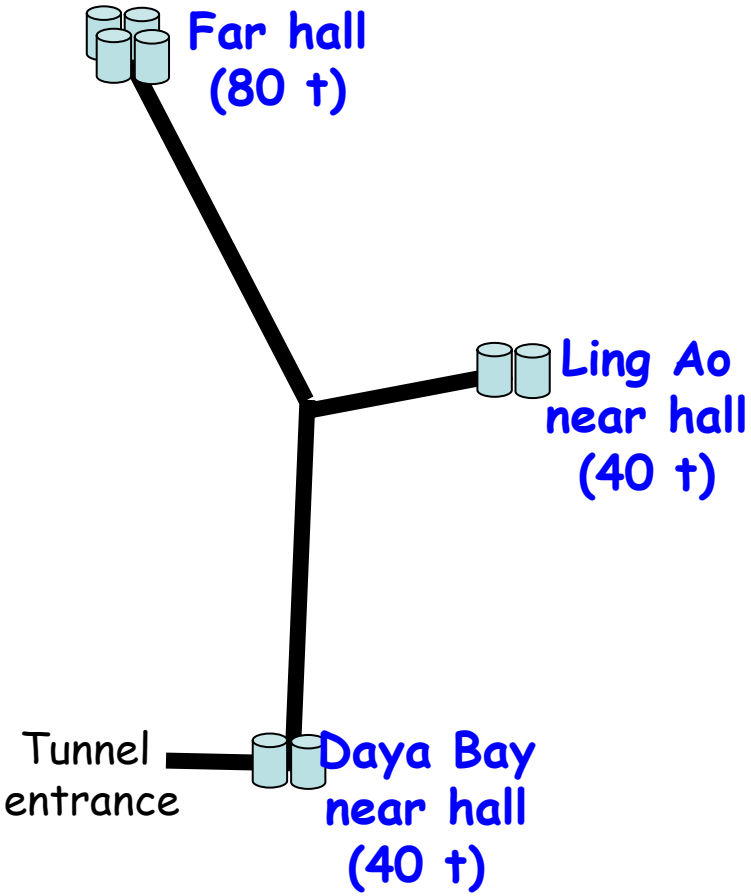
Daya Bay Nuclear Power Facilities

- World's 12th most powerful (11.6 GW_{th})
- 5th most powerful by 2011 (17.4 GW_{th})
- Adjacent to mountains, facilitates tunnels to underground labs with sufficient overburden to suppress cosmic rays (flexibility to move detectors)

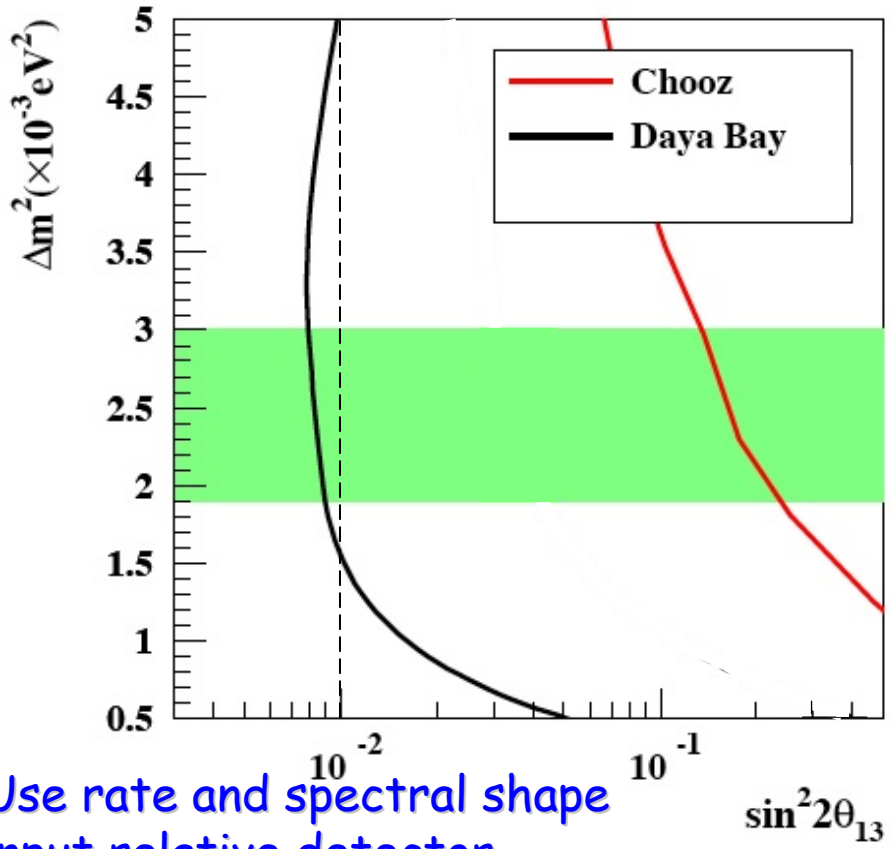



Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.
Ling Ao Near
500 m from Ling Ao
Overburden: 98 m
Mid site
~1000 m from Daya
Overburden: 208 m
910 m
570 m
730 m
290 m
(8% slope)
230 m
(15% slope)
Ling Ao-II NPP
(under const.)
Ling Ao
NPP
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m
Daya Bay
NPP
Total length: ~2700 m
Entrance
portal

Sensitivity



3-year run with 80 t at far site

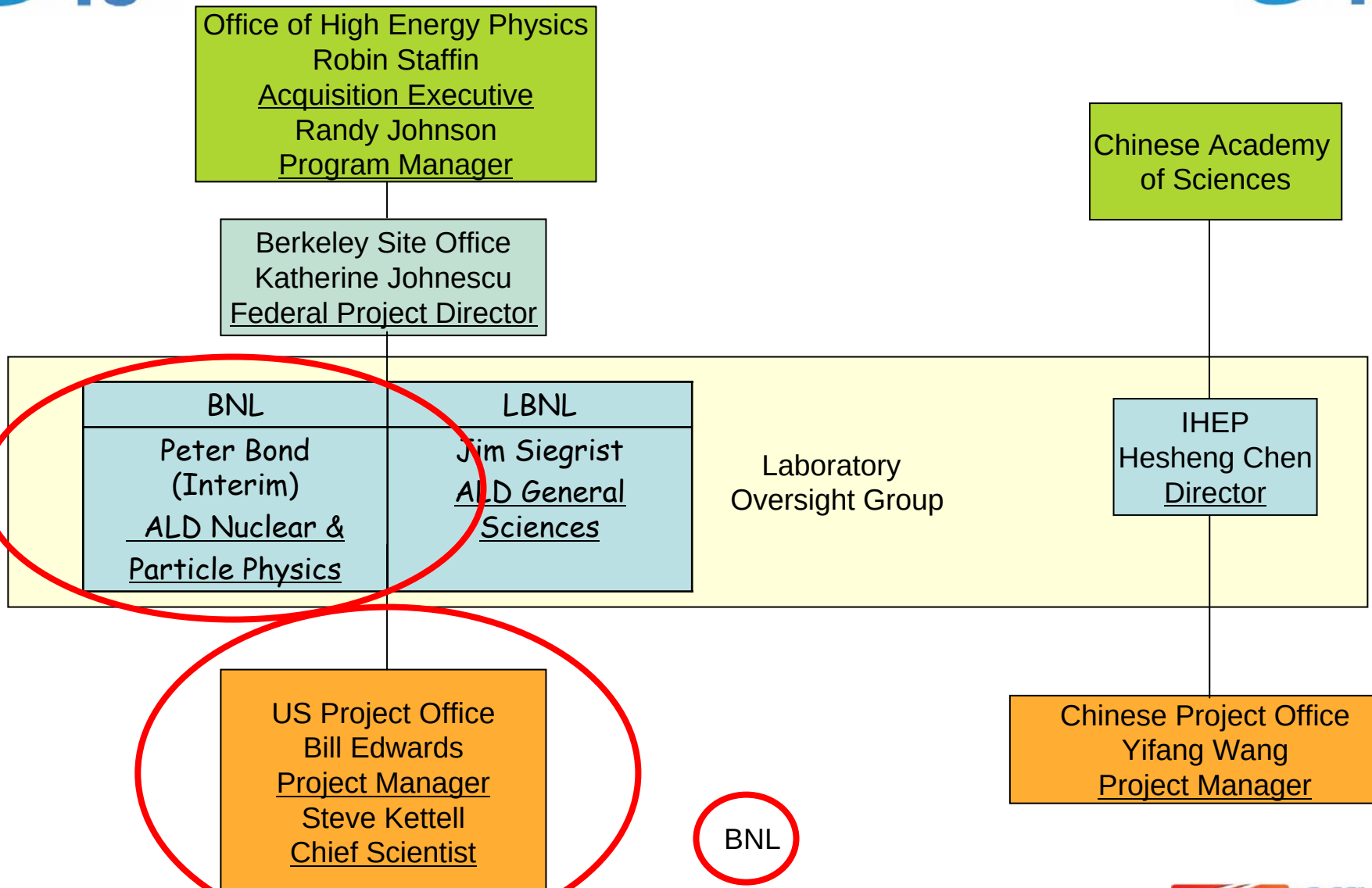


- Use rate and spectral shape
- input relative detector systematic error of 0.2%

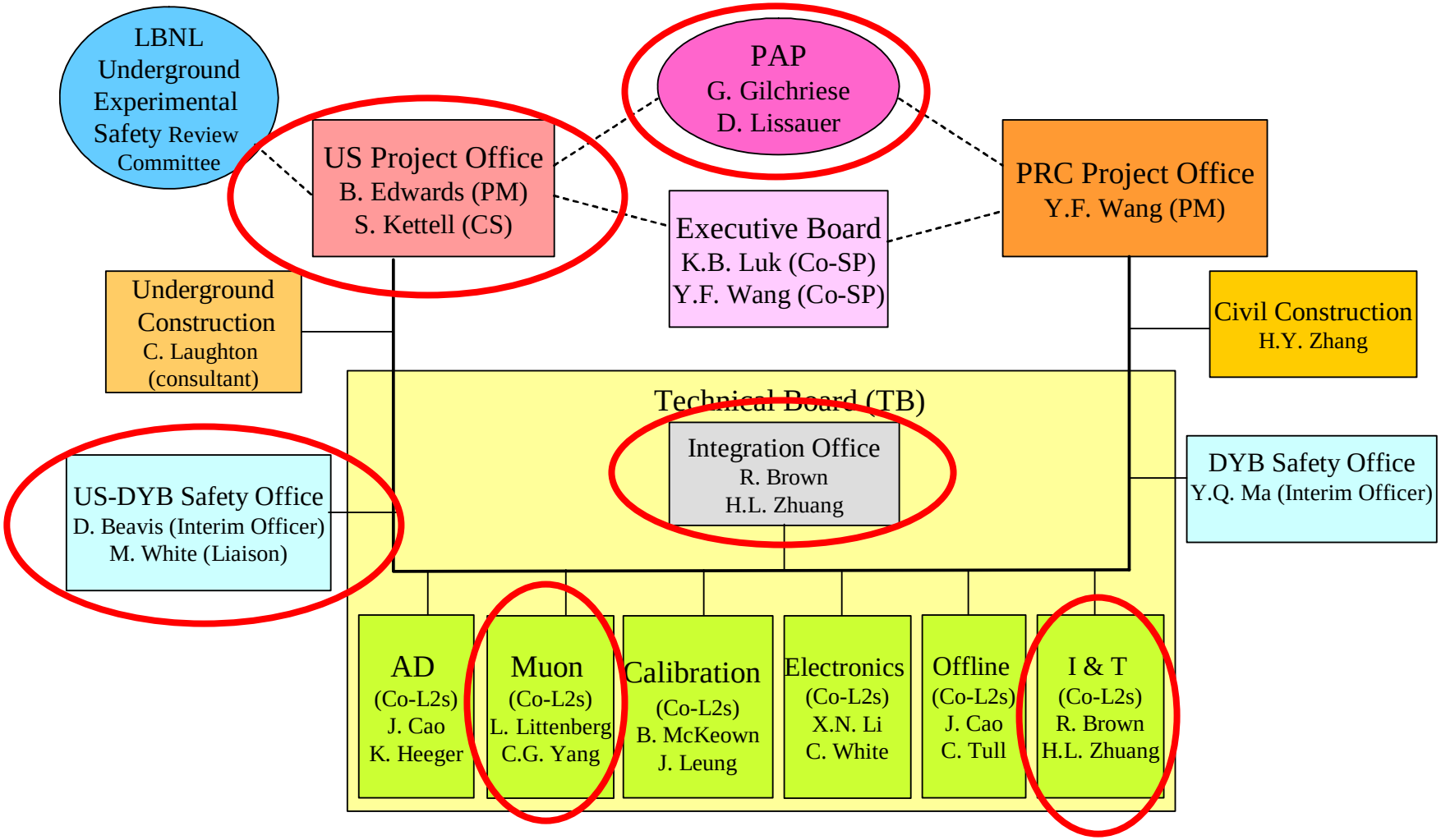
Daya Bay Project Status

- CD-0: 11/2005
- US Daya Bay R&D proposal 1/2006
- BNL formally joins collaboration 2/2006
- Project team assembly begins 2/2006
- NuSAG endorses DB goal and DB expt. as one option 2/2006
- DOE Daya Bay Briefing 4/2006, R&D funds approved
- Successful Physics Review 10/16-17/06
- P5 Roadmap: Recommends Daya Bay 10/2006
- Successful CD-1 Review 4/10-11/07
- Start of Civil construction 7/2007
- CD-2 Baseline planned for 10/2007
- CD-3b Construction start planned for Spring 2008
- CD-4b start of full operations fall 2010

Project/DOE Organization



Internal Project Organization



US Cost Estimate

Daya Bay Project Cost Estimate, FY07 US$

WBS	Description	Base	% Cont	Contingency	Total
1 1	Antineutrino Detectors	8,455,791	36%	3,049,858	11,505,649
1 2	Muon System	3,700,295	22%	806,326	4,506,621
1 3	Calibration & Monitoring	1,939,967	22%	428,733	2,368,700
1 4	Electronics & Online	212,876	12%	26,561	239,437
1 5	Offline	1,364,574	19%	252,969	1,617,543
1 6	Conventional Construction & Equip (PRC)	-			-
1 7	Installation Planning & Support	1,961,186	19%	374,018	2,335,203
1 8	System Integration	1,027,593	20%	203,363	1,230,956
1 9	Project Management	1,766,037	8%	132,975	1,899,012
Management Reserve (TEC)		-		853,692	853,692
Subtotal (TEC)		20,428,318	30.0%	6,128,495	26,556,814
1 10	Prelim Design & Proj Development (OPC)	3,570,809	5%	178,540	3,749,350
Total Project Costs (TPC)		23,999,128	26.3%	6,307,036	30,306,163

=> Peoples Republic of China Project Scope

$31.6M at-year

Major Milestone Summary

- Initial Chinese Funding Secured……. …… Apr&Aug 06
- *CD-1 Review passed…….* *Apr 07*
- Start Tunnel Construction…… July 07
- *CD-2/3a Approval…….* *Nov 07*
- PMT Contract Let…… Nov 07
- *CD-3b Approval…….* *Mar 08*
- AD Hardware in SAB (starting assembly)…… Jul 08
- Beneficial Occupancy of DB Near Hall…… Sept 08
- 1st AD in Filling Hall…… Nov-Dec 08
- DB Near Site Ready to take data…… May 09
- Beneficial Occupancy of LA Near & Far Hall….. Apr & Jul 09
- *CD-4a Approval…….* *Nov 09*
- All Near & Far Sites Ready to Take Data…… Apr 10
- *CD-4b Approval…….* *Sept 10*


Daya Bay Collaboration Meeting
IHEP,Beijing,Feb.13-15,2006

BNL DB Activity in 2006

- **Joined collaboration in February 2006**
- **Led (co-led) task forces:**
  - Simulations: David Jaffe
  - Liquid Scintillator: Dick Hahn
  - Muon Veto: Laurie Littenberg
  - Antineutrino Detector: Steve Kettell
- **Lead role in preparation for the DOE Physics Review.**
  - BNL hosted the Director's Review.
- **Proposal (DOE Physics Review):**
  - leadership in drafting the Trigger/DAQ section
  - leadership of the Muon System section.
  - lead role in the coordination and drafting of the Installation, Operations and Project Development chapters and LS section.
  - lead role in editing and coordinating the Proposal.
- **Coordination of the US effort on the muon system and LS.**
- **Coordination of the US design integration effort.**
- **Lead role in drafting the successful US FY06 R&D proposal.**

Activity at BNL in 2007

- **BNL scientists have key roles in the Daya Bay Project:**
  - Chief Scientist: Steve Kettell
  - Chief Engineer: Ralph Brown
  - Muon System L2 Manager: Laurie Littenberg
  - Installation and Integration L2 Managers: Ralph Brown
  - Liquid Scintillator L3 Manager: Minfang Yeh
  - Analysis and Simulation Software L3 Manager: David Jaffe
  - Co-leader of International Simulation effort: David Jaffe
  - Co-leader of International Liquid Scintillator Task Force: Dick Hahn
- **CDR:**
  - Chair of the Editorial Board and Editor-in-Chief: Steve Kettell
  - Members of the Editorial Board: David Jaffe and Laurie Littenberg
  - Technical advisor to the Editorial Board: Brett Viren
  - Lead Authors of 8 chapters: Steve Kettell, Laurie Littenberg, Ralph Brown.
  - Review committee: D. Jaffe, M. Bishai, B. Viren, R. Brown, L. Littenberg, D. Hahn.
- **BNL is playing a lead role, along with LBNL and IHEP in the engineering design and integration, including the Civil Design specification.**
- **BNL is leading the effort to develop an installation plan**
- **BNL is playing a lead role in developing a Daya Bay safety plan.**

Daya Bay staff at BNL

- BNL Scientific Staff:
  - Physics: 8 people (1 postdoc on LDRD, 1 engineer on DB R&D, 6 scientists on HEP base). Two more scientists involved and planning to join collaboration (supported on NP base). Two additional scientists with minimal involvement (one retired and one on HEP base).
  - Chemistry: 3 people (2 scientists almost supported on base NP, one postdoc supported on LDRD)
  - CAD: 1 person (scientist supported on NP base)
  - Total count of ~14
- FTE count:
  - FY07: 6.4 (3.4 Physics, 2.7 Chemistry, 0.3 CAD. Includes 2 LDRD supported postdocs)
  - FY08R: 7.8 (4.7 Physics assuming postdoc is replaced, 2.7 Chemistry assuming LDRD extension, 0.5 CAD) May add ~1.2 FTE in Physics supported on NP base.

Gd Liquid Scintillator (WBS 1.1.3)

(Chemistry Department)

Gd-LS: A joint US-PRC-Russia activity

Item	Requirement & Justification
long-term chemical stability of Gd-LS	> 3-5 years
high optical transparency for oil, LS and Gd-LS	> 10 m
high photon production for Gd-LS	
ultra-low impurity content	$< 10^{-12}$ g/g
C/H ratio determination	<0.1%
homogeneous distribution of Gd in LS	- thoroughly dissolving and mixing Gd in LS
chemical identity of oil, LS and Gd-LS between each detector module	- single-batch liquid storage for each phase before filling

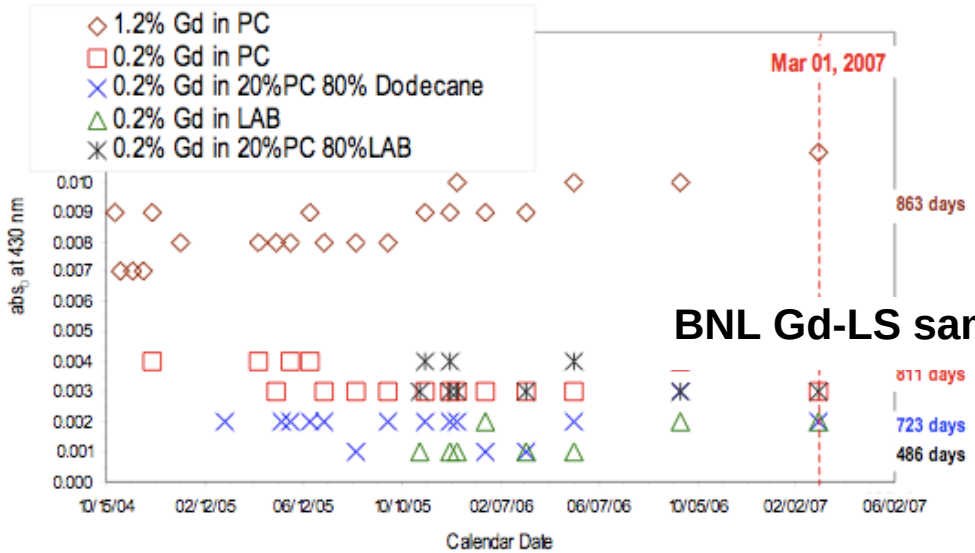


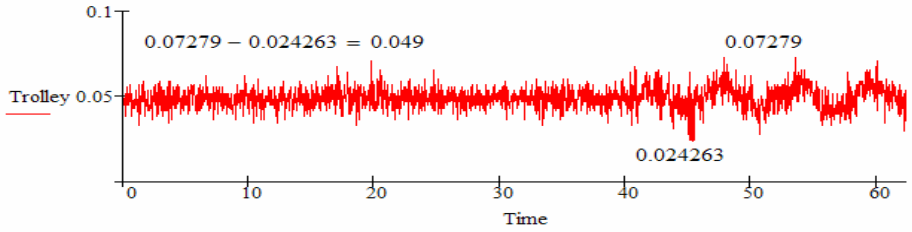
Fig. 6.23. The UV absorption values of BNL Gd-LS samples at 430 nm as a function of time

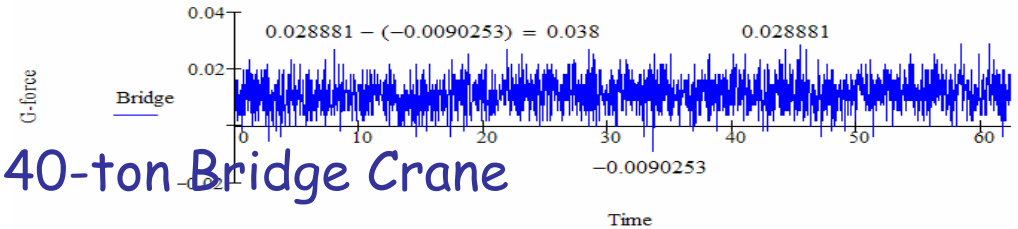
BNL Solvent Extraction

BNL Gd-LS samples

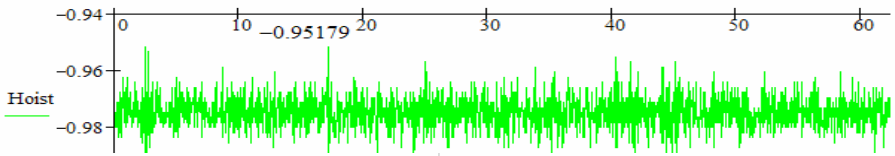
Transporter/Cranes (WBS 1.7)

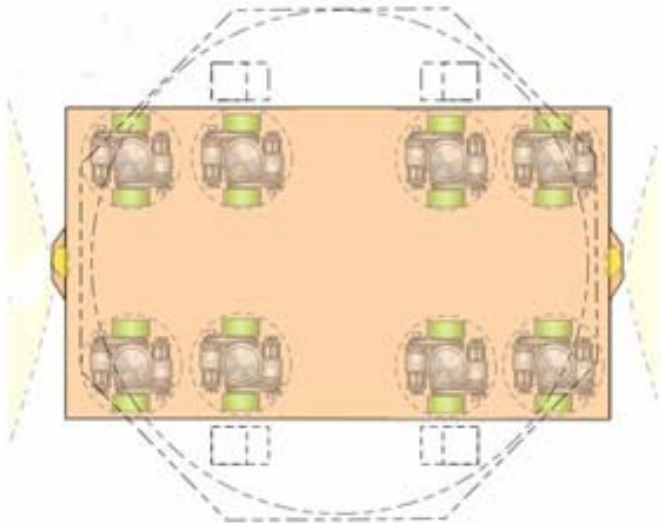
Studies of acceleration



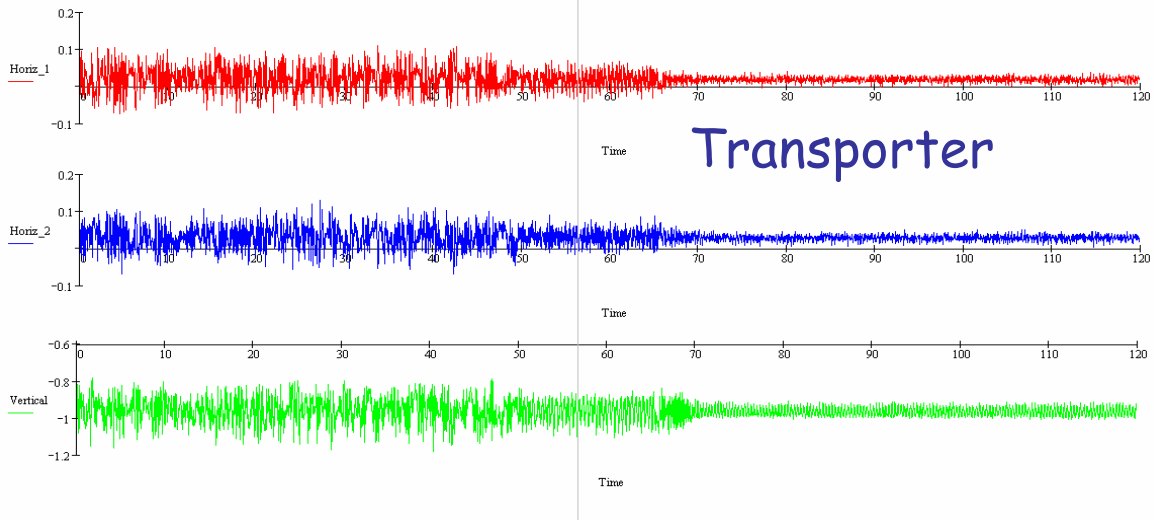


40-ton Bridge Crane





Automatic Guided Vehicle



Transporter

Summary

- The measurement of θ_{13} at Daya Bay is a key part of the US HEP program
- This measurement is important in its own right and to plan future experiments to search for CP violation in neutrinos

  $\rightarrow$ All sites ready to take data 4/10. Measurement by ~2014
- BNL is playing a key role in this experiment and this Project
  - 7 scientists and 1 engineer from Physics
  - 3 scientists from Chemistry
  - 1 scientist from C-AD
  - additional admin and technical support
- Effort has grown from E949/RSVP transfer and BNL LDRD support (plus long term Chemistry involvement – 2004)
- Concerns:
  - There is concern whether we can get a 3-year Project funding profile
  - Concern over NP base support of LS effort
  - Need 1 postdoc (and travel) to replace existing staff!